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Premature Breakdown Identification in Photovoltaic Array Fed IGBT-based Voltage Source Converter

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Insulated gate bipolar transistor (IGBT) is a work element in modern power electronics converters. The ability of the IGBT transistor, which is utilised in power converter circuits, to block high voltages, is one of its most crucial features. Large-scale solar power generations are incorporated into the AC grid via voltage-source converters (VSC). Many other applications also utilise voltage-source converters (VSCs). IGBTs are an integral part of voltage-source converters. Fault in IGBT-based VSCs has an impact on the functionality of all VSC-based systems. So, the fault-proof operation of IGBT is highly desirable. This article presents a methodology to detect the premature IGBT breakdown fault (PIBDF) in a photovoltaic (PV)-grid-connected three-phase three-level Voltage Source Converter (VSC). The work has been done using an analysis that is based on the Fast Fourier Transform (FFT) technique applied to the output phase voltage of VSC. Then for different fault percentage values, the effects on the DC as well as the fundamental frequency component and harmonic distortions have been investigated. Some specific features of the subharmonic components have been studied under the normal and faulty conditions of the IGBT. Further study shows that there are few features suitable for fault identification.

Keywords: Fast Fourier Transform (FFT), Fault Diagnosis, IGBT, PV array, Voltage Source Converter (VSC).

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1. INTRODUCTION

PV systems are an easily accessible sustained technology that can be used for electric power generation and their demand is gradually increasing [1]. Many power devices for both small and substantial usage can obtain the power that is generated from the solar cell using solar energy which is the planet's wealthiest and most environmentally friendly source of renewable energy [1]. Voltage Source Converters (VSCs) are being used in more and more power system applications to increase energy efficiency and power controllability [2-3]. In modern power electronics, IGBT is essential. Because of the involvement of various timeframe dynamics by the VSC's dc-link voltage regulation, the current control loops, and the synchronization of the grid, the stability of VSCs is gaining much attention [2, 4]. In recent days, due to the advances in power semiconductor devices, they are currently a crucial component of contemporary power electronic circuits [5]. Due to the low-current gain of bipolar transistors, the intended circuit's dimensions and weight containing the bipolar transistors significantly increased while placing these in high-voltage fields, therefore the overall system cost also increases [5]. In recent years in many HVDC systems VSCs have been employed [6-8]. In 2019, D. Lu et al. presented different stability problems due to the grid-connected VSCs' dc-link voltage regulation in the article [2]. Sun Xiaoyun et al. in 2016 showed a dissection of the VSC-HVDC converter's fault characteristics [9]. In 2020, X. Sun et al. proposed a fault detection technique for VSC-HVDC converter-based applications [10]. D. K. Ray et al. in 2020 presented a fault detection technique to detect the Line-to-Ground Fault Utilizing Multi-Resolution Analysis in a VSC-Based HVDC System [11]. In 2021, C. Sui et al. [12] proposed the post-fault current model for the detection of the fault of VSC. Quick, accurate fault location determination of a VSC-based distribution network is very important which ensures the operation of the power system is safe and reliable [13]. System faults cause the current to rise rapidly and it also results in a voltage drop suddenly [13]. Generation systems that are VSC based are very much vulnerable to dc faults [14]. In 2021, D. Li et al. proposed a technique for fault detection in DC systems with VSC interfaces based on the S transform (ST) [14]. But no significant attempts were made to detect the IGBT breakdown fault (PIBDF) in Voltage Source Converters (VSCs).

This has motivated authors to diagnose the IGBT-based breakdown fault (PIBDF) in Voltage Source Converters (VSCs). Fast Fourier transform (FFT) is a type of frequency-domain analysis. To distinguish between different transitory kinds the frequency-domain analysis provides better accuracy than the time-domain analysis [14]. Therefore, in this work, FFT has been implemented to detect the PIBDF.

In this work, during PIBDF the VSC's output phase voltage is analysed. Here the voltage signal has been captured for the fault detection purpose because the current signal is greatly affected by the loads but the voltage signal does not have a significant effect due to the loads. Different parameters like the DC component, fundamental component, total harmonic distortion (THD), and sub-harmonic elements of the output phase-voltage of the VSC have been monitored based on the Fast Fourier transform (FFT) to diagnose the fault.

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2. PV-ARRAY DRIVEN IGBT-BASED VOLTAGE SOURCE CONVERTER

A schematic diagram of the grid-connected photovoltaic (PV) array; DC-DC Boost Converter; Maximum power point tracking (MPPT); DC-link; voltage source converter (VSC) has been shown in Fig.1. For modelling purposes, A 100 kW PV array is considered here. The PV array has been connected to a 25 kV grid. A three-phase three-level VSC with a DC-DC boost converter has been used to connect the PV array to the grid. The boost converter employs Maximum Power Point Tracking (MPPT) [15]. To generate the required voltage for the extraction of maximum power the duty cycle can be changed automatically through MPPT system. The harmonics caused by VSC are filtered here using the capacitor bank. Besides the real case study, a MATLAB simulation of the identical Simulink® model was also performed to obtain the PIBDF of VSC.

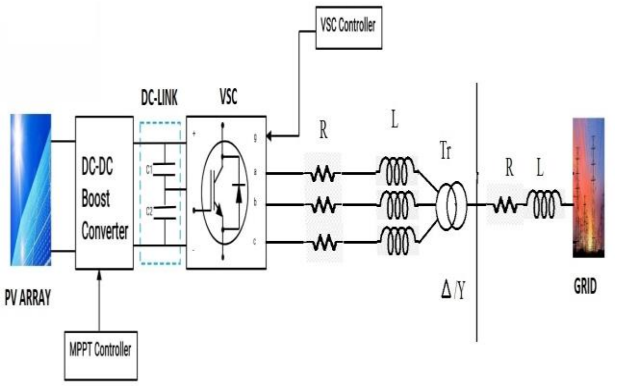

Fig. 1 – Schematic diagram of the grid-connected photovoltaic (PV) array; DC-DC Boost Converter; MPPT controller; DC-link; voltage source converter (VSC), grid.

The photovoltaic array includes a total of 66 parallel strands of 5 series-connected panels, which together generate 100.7 kW of power.

The features of one PV panel are as follows:

A total of 96 cells are connected in series. The open-circuit voltage and short-circuit current of the PV panel are, respectively, 64.2 V and 5.96 A. The PV panel is capable of producing a voltage of 54.7 V and 5.58 A current at maximum power capacity.

For normal conditions and different fault percentage values of the PIBDF in VSC, the phase voltage of VSC has been monitored.

3. PROBLEM STATEMENT

In this work, the IGBT-based VSC is PV-array-driven and utility grid connected. For the fault analysis, the breakdown of the IGBT in VSC is considered. IGBT breakdown is a very unpredictable fault. This fault refers to a breakdown fault and that makes the path open after the fault. It may occur due to an excessive increase of current leading to an increase of heat and burnout of the IGBT or it may occur due increase of voltage leading to insulation breakdown. In both ways, it breaks the circuit that refers to making the path open. In Multi-Terminal DC links during the issue with the DC side, the value of the DC current increases to a very high value, due to this reason the equipment connected across it can be damaged, and the linked VSC systems with it at a common dc terminal, the performance of these also get affected [16]. IGBT loses its control when the VSC HVDC system's dc side fault occurred and as a bridge rectifier, the free-wheeling diodes feed the fault [17]. The protection for IGBTs is excessively complex and difficult, and as a result, they will be destroyed by the heat buildup during the desaturation period when a fault arises and the increasing fault current rate is practically limitless in the early stages of an IGBT fault [6]. Therefore, quick and effective detection of PIBDF is very much required. Hence, an effort has been undertaken in this work to identify the gradual increase in the IGBT breakdown of VSC. It is to be noted that the designer's decision will determine the level of fault and also the system specifications. To prevent the system from being damaged PIBDF detection is very much important.

4. FAULT DIAGNOSIS BASED ON FFT

Fourier Transform (FT), is a useful technique for the analysis of periodic waveforms [18]. In both FT and FFT, the signal is transposed from the time domain to the frequency domain. Also, the FFT is faster than FT [19]. FFT analysis is a very effective tool for determining the precise degree of faults and related frequencies [20]. In this work, during PIBDF in VSC, the VSC's output phase voltage is analysed thoroughly for the detection of PIBDF. Different parameters like the DC element, fundamental element, total harmonic distortion (THD), and sub-harmonic elements of the VSC's output phase voltage have been monitored based on the FFT to diagnose the fault.

4.1 FFT-Based Pattern Generation

FFT analysis has been done on the captured signal of VSC phase voltage under typical circumstances and also during the different percentage values of PIBDF in VSC. Fig. 2 and 3 show the captured signal of VSC phase voltage and the FFT window of the captured signal of VSC phase voltage respectively which are used for the analysis to detect the PIBDF in VSC.

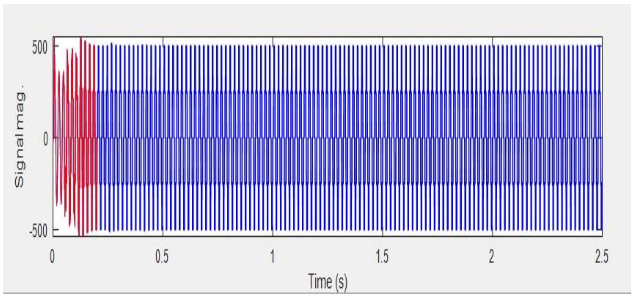

Fig. 2 – Captured signal of VSC phase voltage

Fig. 4 shows the spectrum during normal condition with respect to the fundamental component which has been monitored and analysed for the detection of PIBDF in VSC.

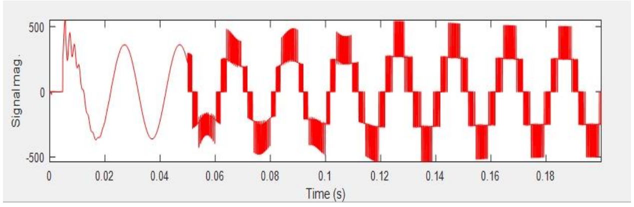

Fig. 3 – FFT window of VSC phase voltage

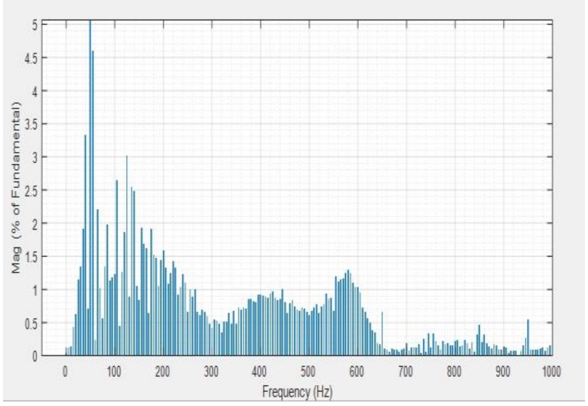

Fig. 4 – Spectrum during normal condition

4.2 Low-Frequency Feature Extractions

4.2.1 DC Component Analysis

The signal of the VSC phase voltage collected has undergone FFT-based analysis so that the DC component can be extracted for different percentage fault values of the PIBDF. From Fig. 5 it can be concluded that the DC components and PIBDF are not directly related.

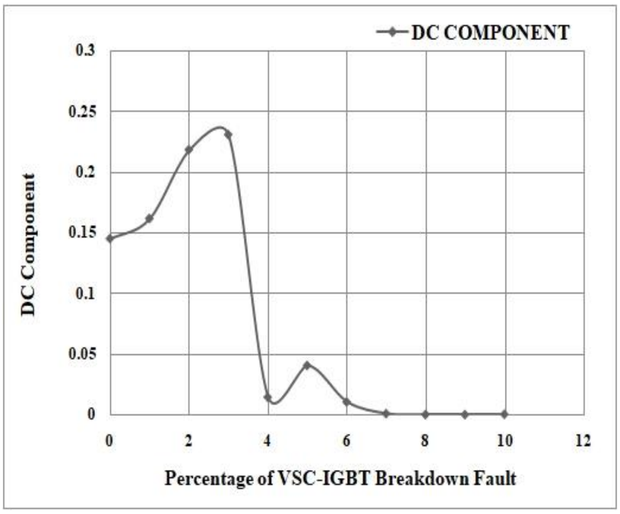

Fig. 5 – DC component versus percentage of PIBDF

4.2.2 Fundamental Voltage Component (FVC)

Fundamental frequency calculation is done here to analyze the frequency distribution of the VSC phase voltage. From the VSC phase voltage for different fault percentage values of the PIBDF, the fundamental component has been extracted and shown in Fig. 6, but it is not providing any proper relationship pattern between the primary frequency of the VSC phase voltage and different fault percentage values of PIBDF.

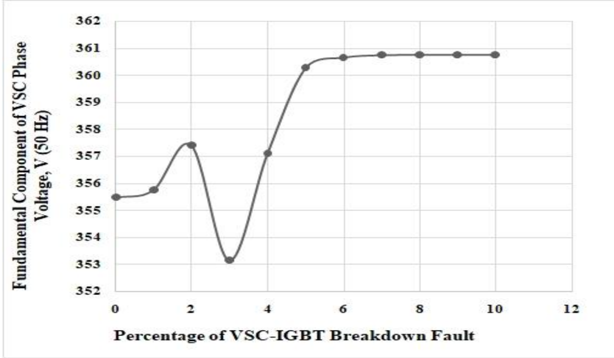

Fig. 6 – FVC versus percentage of PIBDF

4.2.3 Total Harmonic Distortion Analysis

THD of the captured signal determines how much a voltage or current has been distorted by the harmonics within the signal. Expression for THD [19] can be written as follows:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n\_rms}^{2}}}{I_{fund\_rms}}, \qquad (1)$$

Here, I_{n_rms} is the root-mean-square value (RMS) of the harmonic n, and I_{fund_rms} is the RMS value of the fundamental frequency. For different percentages of PIBDF in VSC, here the THD values have been extracted for the analysis of PIBDF and illustrated in Fig. 7. It demonstrates that as there are changes in the percentage fault values of PIBDF, the THD values also vary. A further observation from Fig. 7 reveals that as the percentage of PIBDF in VSC increases up to 3%, the THD(%) value also increases but after 3% of PIBDF, the THD(%) value gradually decreases.

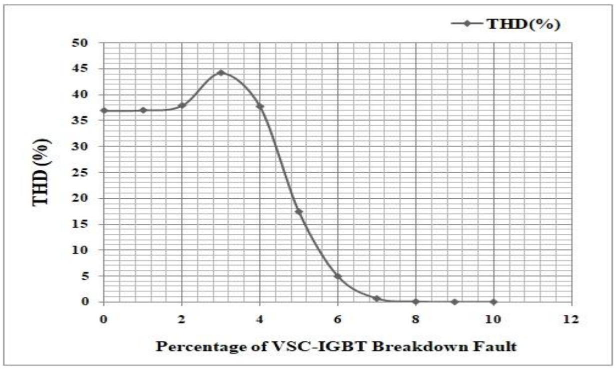

Fig. 7 – Total harmonic distortion (%) versus percentage of PIBDF

4.2.4 Sub-harmonic Voltage Component (SVC)

Sub-harmonic components also have been extracted from the captured VSC output phase voltage signal. All the sub-harmonic components from the captured signal have been thoroughly monitored for different fault percentage values of PIBDF. Fig. 8 shows that as the percentage of PIBDF increases the values of all the values of sub-harmonic components also change.

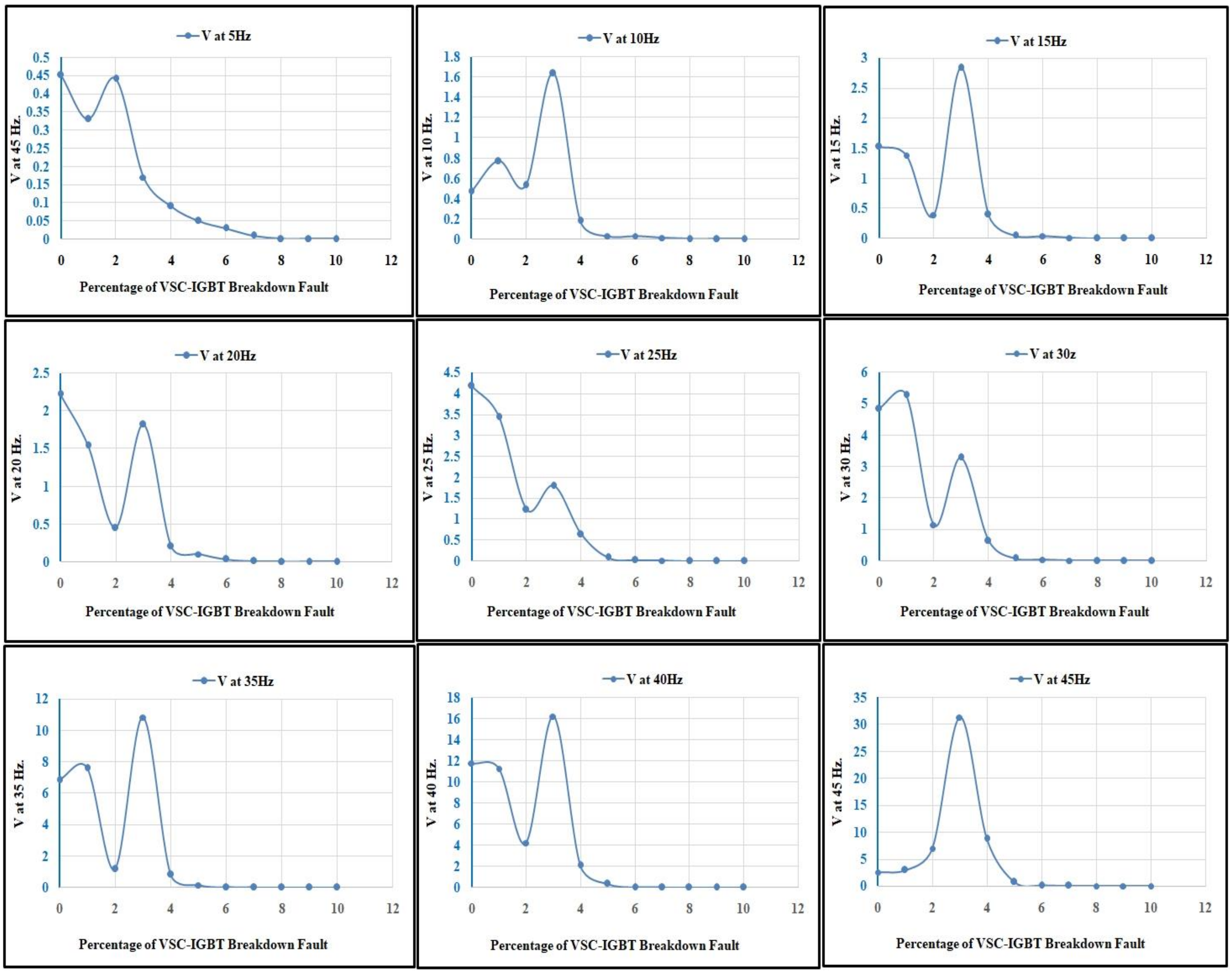

Fig. 8 – SVC versus different percentage fault values of PIBDF

5. SPECIAL FEATURES

In the early section of this work FFT-based signal monitoring has been presented for different parameters like the DC component, FVC, THD, and SVC of the VSC's output phase-voltage but no significant outcome can be obtained which can be used for the detection of PIBDF in VSC.

Further for the analysis of PIBDF, the mean values and the standard deviation values for the change in values of all the sub-harmonic components for different fault percentages of PIBDF have been obtained and presented in Fig. 9. It has been observed that these parameters are changing differently for normal and faulty conditions which can be applied successfully for the detection of PIBDF in VSC up to the 5% of PIBDF. So, it can be inferred that the early detection of PIBDF in VSC is possible with this technique.

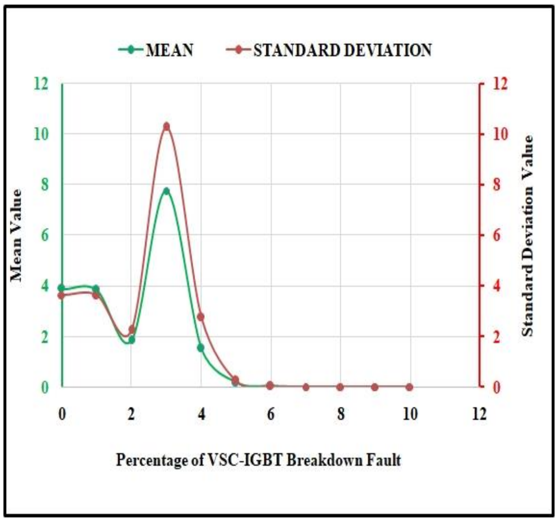

Fig. 9 – Mean and the standard deviation values of the sub-harmonic components vs different percentage fault values of PIBDF

6. CONCLUSION

In this article, for the diagnosis of PIBDF, the statistical analysis using FFT has been performed on the output phase voltage of VSC connected with the PV array and grid. It has been observed that the parameter values differ between them at normal and faulty conditions. With an increase in the PIBDF percentage value, the values of all the parameters change.

Moreover, it was noticed that this flaw detection method based on FFT is efficiently capable of detecting PIBDF early on in VSC. In the future, the DWT-based flaw recognition system may be used may be applied for the fault detection of PIBDF in VSC.

So, by continuous monitoring of measured values, the early detection of PIBDF in VSC can be done. Therefore, the proposed technique can be effectively used for the protection of the system from expensive damages.

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Передчасна ідентифікація поломки в перетворювачі джерела напруги на основі IGBT з фотоелектричною матрицею

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Біполярний транзистор з ізольованим затвором (IGBT) є робочим елементом в сучасних перетворювачах силової електроніки. Здатність транзистора IGBT, який використовується в схемах перетворювача потужності, блокувати високі напруги, є однією з його найважливіших особливостей. Велике виробництво сонячної енергії включається в мережу змінного струму за допомогою перетворювачів джерела напруги (VSC). Багато інших програм також використовують перетворювачі джерела напруги (VSC). IGBT є невід'ємною частиною перетворювачів джерела напруги. Несправність у VSC на основі IGBT впливає на функціональність усіх систем на основі VSC. Таким чином, безвідмовна робота IGBT є дуже бажаною. У цій статті представлено методологію виявлення передчасної несправності IGBT (PIBDF) у фотоелектричному (PV) трифазному трирівневому перетворювачі джерела напруги (VSC), підключеному до мережі. Роботу було виконано за допомогою аналізу, який базується на методі швидкого перетворення Фур'є (FFT), застосованому до вихідної фазної напруги VSC. Потім для різних значень відсотка несправності було досліджено вплив на постійний струм, а також компонент основної частоти та гармонічні спотворення. Досліджено деякі особливості субгармонічних компонентів у нормальних і несправних умовах IGBT. Подальше дослідження показує, що є кілька функцій, придатних для ідентифікації несправності.

Ключові слова: Швидке перетворення Фур'є, Діагностика несправностей, IGBT, Фотоелектрична матриця, Перетворювач джерела напруги (VSC).